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# Ecological efficiency and thermoeconomic analysis of a cogeneration system at a hospital

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ABSTRACT

This work aims with an approach for cogeneration plants evaluation based on thermoeconomic functional diagram analysis. The second law of thermodynamics is used to develop a methodology to analyse cogeneration systems, based on exergoeconomics evaluation. The thermoeconomic optimisation method developed is applied to allow a better configuration of the cogeneration plant associated to a university hospital. Also ecological efficiency is evaluated. The method was efficient and contributes for thermoeconomics modelling and analysis and can be applied to any sort of thermal system, especially those with combined heat and power in thermal parity.



**Contents**



## 1. Introduction

The successive energy crises have stimulated the study of more efficient ways for the use of the available energy in fuels. As consequence new technical plants have been conceived seeking the primary energy conservation. Cogeneration may be defined as the simultaneous production of electrical or mechanical energy and useful thermal energy from a single energy source, such as oil, coal, natural or liquefied gas, biomass, or solar. By capturing or applying heat from an effluent energy source that would otherwise be rejected to the environment, cogeneration system can operate at efficiencies greater then those achieved when heat and power are produced in separate or distinct processes. Recovering this thermal energy for a useful purpose from reciprocation engines or steam or gas turbines.

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Several works based on development of methodologies to model and to optimise thermal energy systems had been looked up to obtain information about techniques used in these evaluations [1–7].

Development of models for thermoeconomic design and operation optimisation had also evaluated. These works appoints to thermoeconomic optimisation and the best way to obtain the balance between exergy balance and energy production/generation costs [8–15].

Thermoeconomics had been explained through several works that relate exergy balance analysis and costs minimization. This literature was important to materialise basic fundamentals that are very important to develop the proposed methodology [16–23].

Thermoeconomics is nowadays a powerful tool to study and optimise an energy system. In its application field is the evaluation of utility costs as products or supplies of production plants, the energy costs between process operations or of an energy converter. Those costs are applicable in feasibility studies, in investment decisions, on comparing alternative techniques and operating conditions, in a cost-effective section of equipment during an installation, and in an exchange or expansion of an energy system [24–26].

In [24,27], the thermoeconomic analysis was presented in a linear programming level, according to the matrix method presented by [28], as a criterion for cogeneration systems selection with use of steam turbine and/or gas turbine. In this work, the fuel type (oil, natural gas or wood) was one of the main decision parameters. In this type of analysis were studied three alternatives for energy supply to an industrial process, allowing the determination of the exergetic flows, the second law efficiency of the equipments and the costs of the products supplied to the industrial process (steam and electricity). The simulations had demonstrated that the technology using natural gas is economically competitive in comparison to others technologies.

Another model that considers the use of Lagrange multipliers with non-linear programming characteristics, developed by [29,30], was presented by [31,32] where the pressure and temperature of live steam produced in boilers were the decision variables. In this case, the optimisation of a cogeneration system using condensing steam turbine with two extractions was discussed and used as a technique for efficient production of electricity and steam for the pulp industry. Thus, conditions that led to the lower cost for purchase and operation of the cogeneration plant were determined according to the Lagrangian function minimization, incorporating the operation and investment costs.

Gaggioli [33] and El-Sayed [34] suggested evaluation methods with fewer difficulties. In some way to guarantee the applicability of considering mathematically the exergy composed solely by thermodynamic components.

The aim of this paper is to develop a thermoeconomic optimisation method for the energy systems treatment through the use of a simple mathematical model based on graphical representation for the interface through subsystems from a cogeneration plant. This method addresses economic aspects associated with the exergy conception, in order to develop a tool to assist the equipment selection, operation mode choice, as well as to optimize the thermal plants design. The idea is to develop an algebraic method, based on associated costs analysis suggested by [35–38] with the exergetic analysis.

Aspects of thermal design through second law of thermodynamics were reviewed before. In these developments were studied features such as background, algebraic and calculus procedures for costing methods in exergoeconomic theory. Also techniques for identification and optimisation of thermal system components were also viewed [29,30,33,34,40].

Exergy concepts associated to thermal plants were reviewed through [28,41–43], such as performance criteria, analysis methods, and exergy costs.

Thermoeconomics applied to cogeneration systems had studied through [24,31,35–37]. Thermoeconomic functional analysis applied to cogeneration plants had focused by these authors. Features as criterion for selection, comparison of use of different fuels in cogeneration plants, and small solution for specific cases were also studied.

Wall [44] studied optimisation of refrigeration machinery, such as absorption machines used in this work.

## 2. The energy requirements and the cogeneration system

This case-study shows cogeneration alternatives to supply the energy demand (operating in thermal parity) of "Hospital de Clinicas Barao Geraldo", from University of Campinas, using an alternative internal combustion engine (AICE). This hospital has 400 rooms, was built on a 60,000 m$^2$ area, with 3000 people working there, and around 100 people are attended per day.

In this hospital, there are two electrical substations those are supplied by a 11.9 kV power grid. The electric power installed is 5.8 MW, where the amount of 2 MW corresponds to power purchased. These electrical substations distribute electricity in two levels according to consumption class: 220 V or 380 V. The electricity demand is consumed in illumination and driving of medical-hospital equipments and machinery, such as air-conditioning system by steam compression, pumps and etc.

In case of power grid supplying interruption, the hospital has two diesel generators with 400 kW$_e$ each one, which maintain surgical centre, emergency laboratory, intensive care unit, and a part of illumination. According to [39], the medium monthly electric consumption had been 77,268 kW h at peak (three hours a day) and 763,030 kW h off peak, with a medium power factor of 0.87.

Around 30% of all electric energy consumed is destined to air-conditioning system, which is based on steam compression cycle (electric chiller).

The fuel oil of low pour point (LPP) is used as fuel to produce saturated steam in boilers. The hospital had been consumed 1.085 t. The kerosene is used to start steam generators (boilers). Its medium monthly consumption is 5000 l. The liquefied petroleum gas (LPG) is the fuel used directly in cooking stoves. Its medium monthly consumption is 9587 kg.

There are three 0.75 MPa boilers to produce saturated steam. Only one is need to attend the hospital demand, with other one held as stand-by, and the last one in mechanical maintenance.

There are four chillers that have a total capacity of 700TR (or 2506 kW$_c$), which produces cold water at 7 °C to be used in air-conditioning system. Those chillers work according to Freon compression cycles and they agree with operating data. Their coefficient of performance (COP) for compression air-conditioning system is 3.8.

The hospital has two boilers to produce hot water (water-steam heat exchanger), where water enters around 25 °C and leaves around 60 °C, being heat up in the serpentine where steam flows.

Fig. 1 shows the simplified scheme of hospital machine house that is studied through this work.

## 3. Cogeneration systems proposed

In order to develop this study, it will be elaborated four different plants that will be depicted in function of equipment type for residual heat recovery.

The study of cogeneration alternatives capable to fill up hospital energy demand (working in thermal parity) through AICE use is the

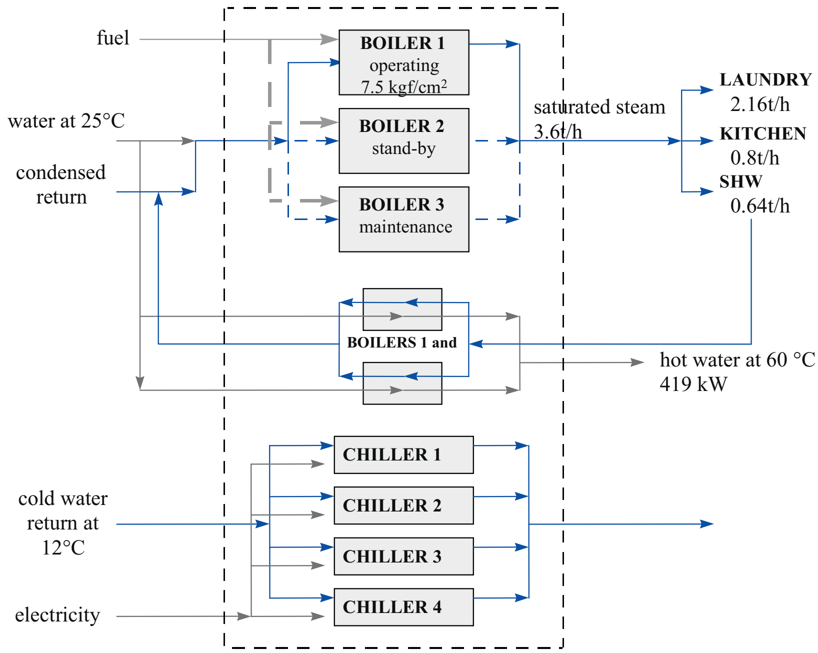


**Fig. 1.** Utilities centre of the hospital.

goal of this work. In this way, there were studied four cases based on different equipment set for residual heat recovery. These scenarios are described below:

- case 1: AICE with natural gas associated to a residual heat recovery steam generator (HRSG) and steam generation boundary of 2960 kg/h, corresponding to kitchen and laundry demands, respectively 524 kW and 1416 kW;
- case 2: AICE with natural gas associated to a residual HRSG and steam generation boundary of 800 kg/h, corresponding to kitchen needs;
- case 3: AICE with natural gas associated to a residual HRSG and steam generation boundary of 2160 kg/h, corresponding to laundry needs;
- case 4: AICE with natural gas associated to an absorption refrigeration system with direct use of exhaust gases to produce cold water at 7 °C replacing electric chillers, corresponding to a capacity of 700TR (2506 $kW_c$).

The four cases proposed correspond to only two cogeneration technologies. The difference between these two technologies is that the first technology appoints to use the residual heat from exhaust gases to produce steam in an HRSG (cases 1, 2, and 3) and the other one uses the same residual heat from exhaust gases to produce cold water in an absorption machine (case 4).

In all cases, AICE systems (commercially available) were dimensioned in function of exhaust gases demand required. The residual heat from AICE refrigeration water was used to produce hot water for the hospital. Table 1 shows technical assumptions established.

The engines selected, obeying thermal parity operating criteria and according to proceedings related by [45], are from Fairbanks Morse manufacturing.

Fig. 2 shows diagram for cogeneration systems using AICE associated to HRSG (cases 1, 2, and 3).

Fig. 3 shows diagram for cogeneration system case using AICE associated to absorption machine.

In this last scenario is appropriate to consider two technical possibilities: in first, named case 4a, a simple effect (one stage) absorption refrigeration system is jointed (COP = 0.65) and in other one, case 4b, a double effect (two stages) system is used (COP = 1.2). Table 2 shows the features of the engines choose for each scenario.

## 4. Economical analysis

Based on methodology developed by [39] for cogeneration products costs evaluation, it is possible to analyse production costs of electricity, steam, cold water, and hot water, in cogeneration systems.

Eq. (1) represents objective function for thermoeconomic optimisation problem of cogeneration system, where to obtain the exergetic production cost (EPC) from small station products costs is the goal.

$$\mathrm{EPC\,(US\$/kW\,h)} = \sum_{i=1}^{n} C_i Y_{i,k} \quad \text{for } k = 1 \text{ to } n \tag{1}$$

Cost of electricity generation:

$$C_e = \frac{I_{pl} - I_{hrsg} - I_{he}}{H \times E_P} + c_{fuel}\frac{E_{fuel} - E_{hrsg} - E_{cw} - (\mathrm{losses}/2)}{E_P} + C_{Men} \tag{2}$$

Cost of steam production:

$$C_s = \frac{I_{hrs\dot{g}}}{H \times E_{sr}} + c_{fuel}\frac{E_{hrsg} - (\mathrm{losses}/2)}{E_{sr}} + C_{Mhrsg} \tag{3}$$

**Table 1**
Technical parameters and assumptions considered.

| | |
|---|---|
| Conventional boiler efficiency | 85% |
| Heat recover efficiency | 70% |
| Condensed return temperature | 97 °C |
| Environmental air temperature | 25 °C |
| Water utility temperature | 25 °C |
| Sanitary hot water (SHW) demand | 419 kW (0.64 t/h) |
| Electricity demand with actual compression air-conditioning equipment | 2 MW |
| Electricity demand with new absorption machine | 1.5 MW |

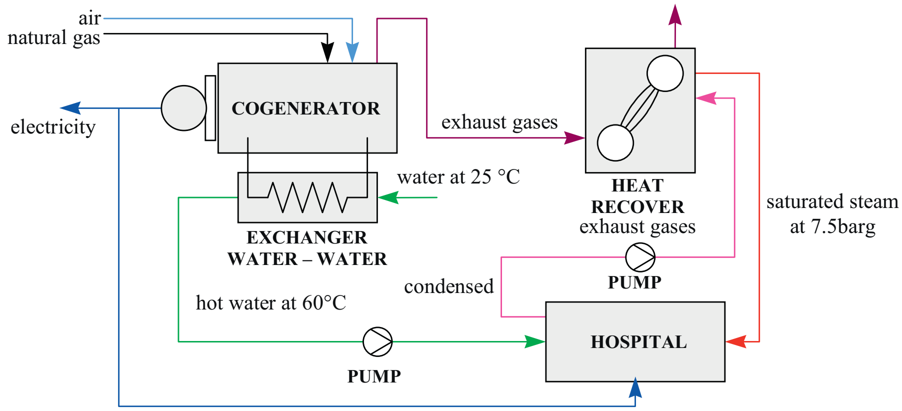


**Fig. 2.** Cogeneration system with AICE and recovery boiler.

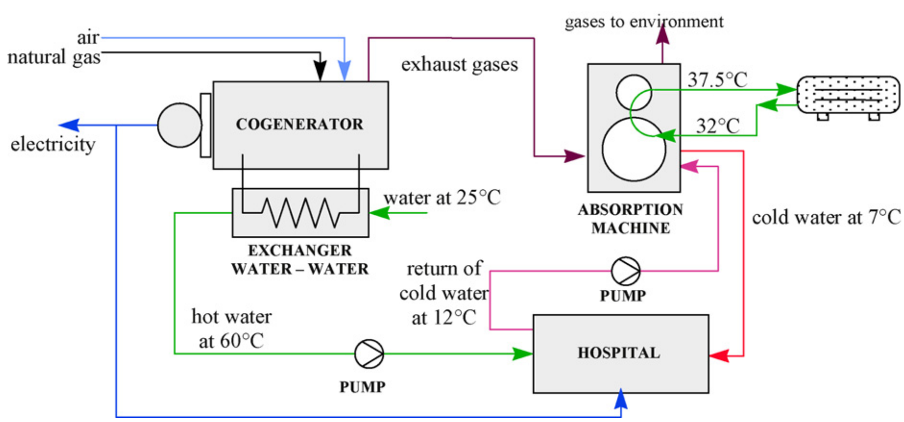


**Fig. 3.** Cogeneration system with AICE and absorption machine.

Cost of cold water production:

$$C_{cw} = \frac{I_{am}}{H \times E_{cold}} + c_{fuel} \frac{E_{hrsg} - (\text{losses}/2)}{E_{cold}} + C_{Mam} \quad (4)$$

Cost of hot water production:

$$C_{hw} = \frac{I_{he}f}{H \times E_{cw}} + c_{fuel} + c_{Mhe} \quad (5)$$

The annuity factor ($f$) can be determined for Eqs. (2)–(5) such as Eq. (6).

$$f = \frac{q^k(q-1)}{q^k - 1} \quad (6)$$

with:

$$q = 1 + \frac{r}{100} \quad (7)$$

The investment costs for AICE (including electricity generators, control systems, inertia base, etc.), absorption machines, and water–water exchangers, follow all trade prices:

$$I_{en} = -336 + 0.531 \times E_p \,(\text{US\$}) \quad (8)$$

$$I_{am} = 200\,(\text{US\$/kW}_e) \quad (9)$$

$$I_{he} = 10\,(\text{US\$/kW}_e) \quad (10)$$

According to [46], for the case of AICE investment, such as Eq. (8), electricity generated ($E_P$) must be in kW (this affirmation is valid for the range between 1300 kW and 4000 kW). In the case of double effect (COP = 1.2) absorption machine investment is considered an improvement of 20% for the value of Eq. (9).

In the case of investment in HRSG without supplementary fuel burning, according to [39,47], Eq. (11) is valid for production values between 800 kg/h and 4000 kg/h, being estimated 10% of investment value as installation cost.

$$I_{hosg} = 1.1 \times 160,000 \left(\frac{\dot{m}_s}{1500}\right)^{0.81} (\text{US\$}) \quad (11)$$

**Table 2**
Selected engines.

| | Model | rpm | Unit no. | Features for each unit | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Exhaust temp. (°C) | Gases flow (kg/s) | Electric energy (kW) | Heat, water + oil (kW) | Fuel energy (kW) |
| Case 1 | 38ETDS8-1/8 | 900 | 2 | 338 | 6.26 | 2,585 | 1,224 | 7,526 |
| Case 2 | 38TDS8-1/8 | 720 | 1 | 310 | 3.40 | 1,370 | 1,461 | 4,013 |
| Case 3 | 38ETDS8-1/8 | 720 | 2 | 338 | 5.01 | 2,060 | 979 | 6,020 |
| Case 4a | 38ETDS8-1/8 | 900 | 3 | 338 | 6.26 | 2,585 | 1,224 | 7,526 |
| Case 4b | 38ETDS8-1/8A | 900 | 2 | 338 | 5.22 | 2,150 | 1,019 | 6,271 |

**Table 3**
Assumptions for economical analysis.

| | |
|---|---|
| Interest rate ($r$) | 12% |
| Payback period ($k$) | 5 years |
| Annuity factor ($f$) | 0.277 |
| Heat recover efficiency ($\eta_{hr}$) | 70% |
| Central's equivalent period of utilization ($H$) | 7000 |
| Cost of fuel-natural gas ($c_{fuel}$) | 0.011 US$/kW h |
| Cost of fuel-FLP ($c_{oil}$) | 0.013 US$/kW h |
| Electricity purchase price ($c_{ep}$) | 0.070 US$/kW h |
| Surplus electricity sale price ($c_{sur}$) | 0.035 US$/kW h |

Also according to [39], maintenance costs for cogeneration system equipments can be evaluated by Eqs. (12)–(15).

AICE maintenance cost:

$$C_{Men} = 0.013\,(\text{US\$/kW h}) \tag{12}$$

HRSG maintenance cost:

$$C_{Mhrsg} = 0.1 \times \frac{I_{hrsg} f}{H \times E_{sr}}\,(\text{US\$/kW h}) \tag{13}$$

Absorption machine maintenance cost:

$$C_{Mam} = 0.1 \times \frac{I_{am} f}{H \times E_{cold}}\,(\text{US\$/kW h}) \tag{14}$$

Water–water heat exchanger maintenance cost:

$$C_{Mhe} = 0.05 \times \frac{I_{he} f}{H \times E_{cw}}\,(\text{US\$/kW h}) \tag{15}$$

In the reference, or conventional, scenario, there is a central unit that produces only steam. The electricity is bought from local utility company. The hot water is produced through boilers and the cold water is produced through chillers. Therefore, reference costs are described in Eqs. (16)–(21).

The cost of steam production in conventional boiler is

$$c_{scb} = \frac{I_{cb} f}{H \times E_{sr}} + \frac{c_{oil}}{\eta_{cb}} + c_{Mcb}, \tag{16}$$

where

$$I_{cb} = 2 \times 1.4 \times 16,000 \left(\frac{\dot{m}_s}{1000}\right)^{0.64}\,(\text{US\$}) \tag{17}$$

and

$$c_{Mcb} = 0.1 \times \frac{I_{cb} f}{H \times E_{sr}}\,(\text{US\$/kW h}) \tag{18}$$

The cost of cold water production in electric chiller is

$$c_{cwec} = \frac{I_{cr} \times f}{H \times E_{cold}} + \frac{c_e}{COP} + \frac{c_{Mcr}}{H \times E_{cold}} \tag{19}$$

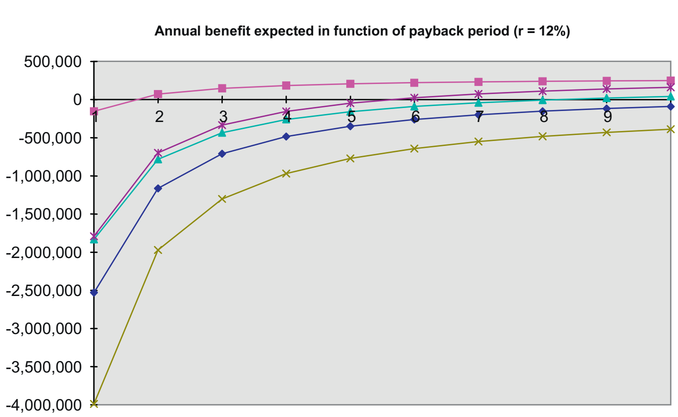


**Fig. 4.** Annual benefit in function of payback period.

**Table 4**
Values of investment and maintenance.

| Case # | Investment | | | | Maintenance | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | AICE ($I_{en}$) (US$) | HRSG ($I_{hrsg}$) (US$) | Absorption machine ($I_{am}$) (US$) | Hot water recovery system ($I_{hwrs}$) (US$) | Cogeneration plant ($I_{pl}$) (US$) | AICE ($c_{Men}$) (US$/kW h) | HRSG ($c_{Mhrsg}$) (US$/kW h) | Absorption machine ($c_{Mam}$) (US$/kW h) | Hot water recovery system ($c_{Mhwrs}$) (US$/kW h) |
| 1 | 2,409,270 | 290,874 | 0 | 54,181 | 2,754,326 | 0.013 | 0.000631 | 0.000000 | 0.000256 |
| 2 | 391,470 | 84,542 | 0 | 14,611 | 491,623 | 0.013 | 0.000843 | 0.000000 | 0.000069 |
| 3 | 1,851,720 | 236,161 | 0 | 36,356 | 2,124,236 | 0.013 | 0.000662 | 0.000000 | 0.000172 |
| 4a | 3,781,905 | 0 | 501,200 | 59,439 | 4,342,544 | 0.013 | 0.000000 | 0.000793 | 0.000281 |
| 4b | 1,947,300 | 0 | 601,440 | 39,086 | 2,587,826 | 0.013 | 0.000000 | 0.000951 | 0.000185 |

According to [46], Eq. (20) defines $I_{cr}$ and is valid to frigorific power between 20 kW and 5000 kW, with maintenance cost associated such as Eq. (21).

$$I_{cr} = 267,000\left(\frac{E_{cold}}{1000}\right)^{0.77} \text{(US\$)} \tag{20}$$

and

$$c_{Mcr} = 8000\left(\frac{E_{cold}}{1790}\right)^{0.42} \text{(US\$)} \tag{21}$$

The annual benefit or receipt dues to cogeneration plant installation is obtained by sum of profits associated to electricity and useful heat production. If this value was negative means that costs associated to cogeneration plant are bigger than costs associated to conventional attendant systems (reference scenario, utility company electricity, and conventional equipment thermal energy).

In the case of electricity surplus exportation, there is that:

$$Pd_e = E_r \times H(c_{ep} - c_e) + (E_p - E_r) \times H(C_{sur} - c_e) \tag{22}$$

If the cogeneration plant is working with electricity deficit, in such a way that electricity required is bigger than electricity produced, is valid that:

$$Pd_e = E_{\dot{p}} H(c_{ep} - c_e) \tag{23}$$

In other way, the profit due to steam production is

$$Pd_s = E_{s\dot{r}} H(c_{scbl} - c_s) \tag{24}$$

The profit due for hot water production is

$$Pd_{hw} = E_{h\dot{w}} H(c_{scb2} - c_{hw}) \tag{25}$$

The annual receipt expected for cases 1, 2, and 3 is

$$R = Pd_e + Pd_s + Pd_{hw} \tag{26}$$

In case of cold water production by the system (cases 4a and 4b), the profit dues for this one is evaluated through Eq. (27) and its annual receipt expected through Eq. (28).

$$Pd_{cw} = E_{cold} \times H(c_{cwec} - c_{cw}) \tag{27}$$

$$R = Pd_e + Pd_{cw} + Pd_{hw} \tag{28}$$

Table 3 shows assumptions adopted for economical analysis of cogeneration systems proposed for the hospital.

Variation of distinct parameters will be effectuated in some points with intention to observe the sensibility of these factors according to economic viability for installations.

Investment values (funds and installation) and maintenance costs are showed in Table 4, while cogeneration products costs are showed in Table 5.

Values of investment and maintenance for conventional equipment case are showed in Table 6 and associated products values are showed in Table 7.

Table 8 shows annual profits and benefits expected, considering five years for payback period and an interest rate of 12% per year. Observe that in this situation, only case 2 (unique operating with electric energy slack) is profitable. This is because the price adopted to sale electricity surplus is 0.035 US$/kW h, very low in comparison with production cost.

Maintaining annual interest rate at 12% and surplus electricity sale price at 0.035 US$/kW h, it is possible to observe, Fig. 4, the influence of payback period in the annual benefit expected.

The Case 2 is the most profitable of four scenarios, presenting a payback period of 1.8 year.

It is possible to observe the influence of interest rate over annual benefit considering a payback period of five years, such as showed in Fig. 5.

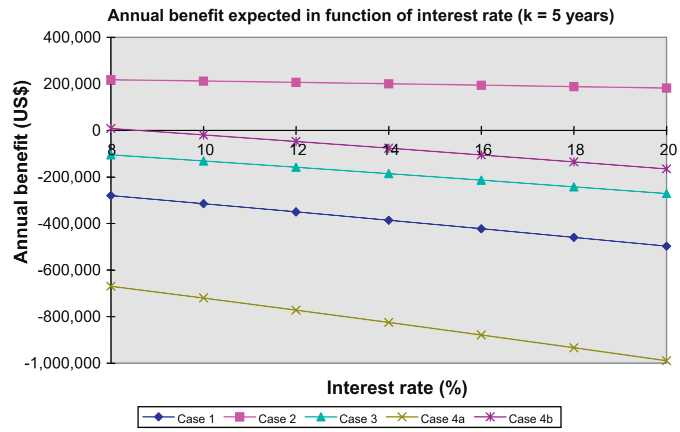


**Fig. 5.** Annual benefit in function of interest rate.

Case 2 is still economically viable and case 4b also can be it for an interest rate of 8.5% per year. For the payback period considered (five years) the other scenarios are not recommended.

Fig. 6 shows influence of surplus electricity sale price and payback period ($k$) over economically viable investment.

## 5. Application of thermoeconomic method to the hrsg cogeneration plant

### 5.1. System function identification—process diagram

The first stage of exergoeconomic analysis used in this topic consists in draft a cogeneration plant diagram that makes possible to view all components and material flows related to it. It is important to indicate by numbers all plant components and flows (materials, energies and exergies associated to this plant), such as showed in diagrams of Figs. 7 and 8, which will provide to understand the optimisation problem formulation that follows.

It must be observed only the useful energy that was produced through cogeneration system was studied. In an exergetic analysis, it must necessary to consider components that dissipate heat without using it.

Tables 9 and 10 show features of flow, temperature, pressure, specific enthalpy, and specific entropy for each numbered point in Figs. 7 and 8, respectively.

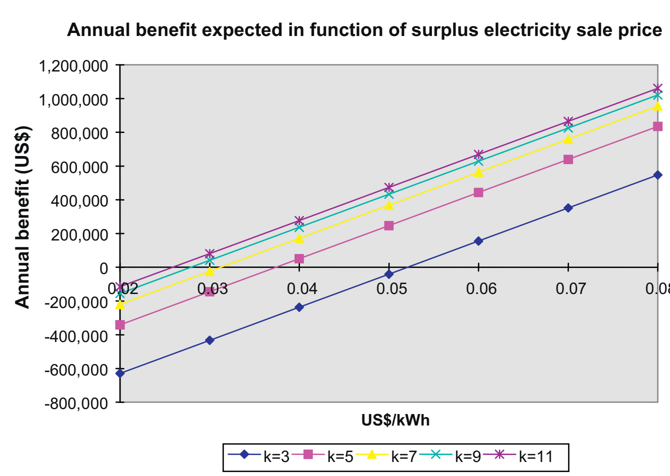


**Fig. 6.** Benefit in function of surplus electricity sale price and payback.

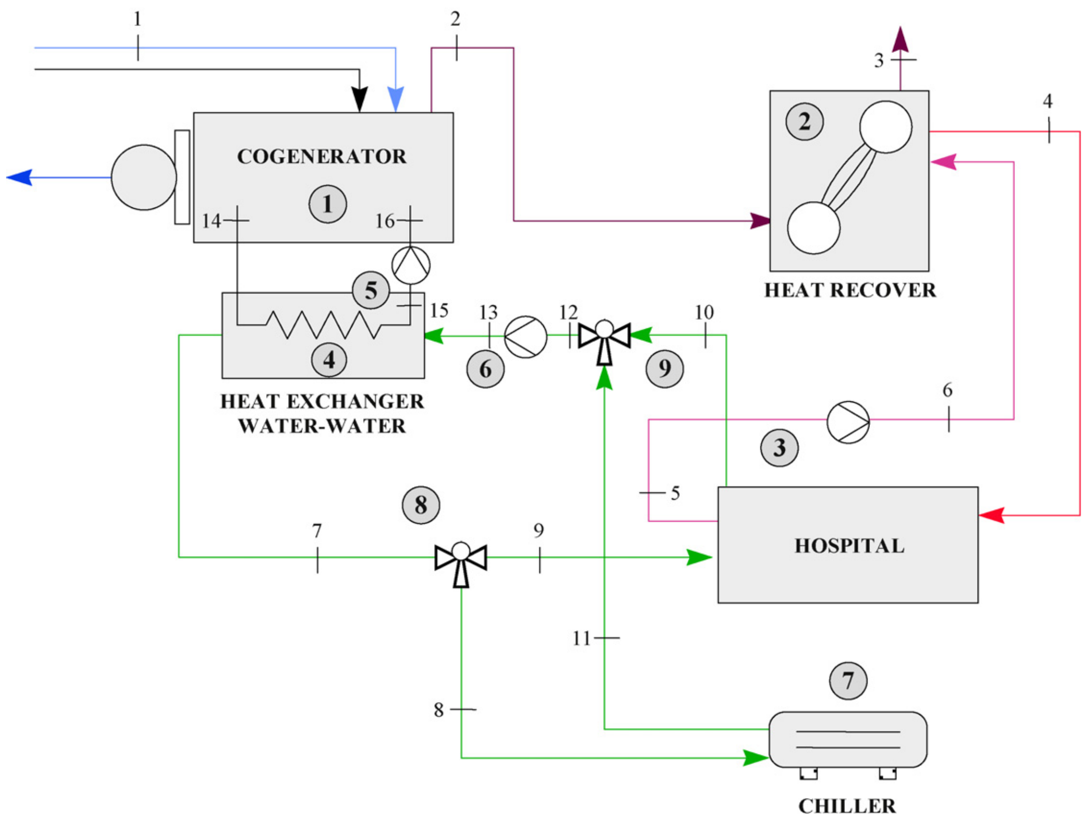


**Fig. 7.** Diagram of cogeneration plant using AICE and recovery boiler.

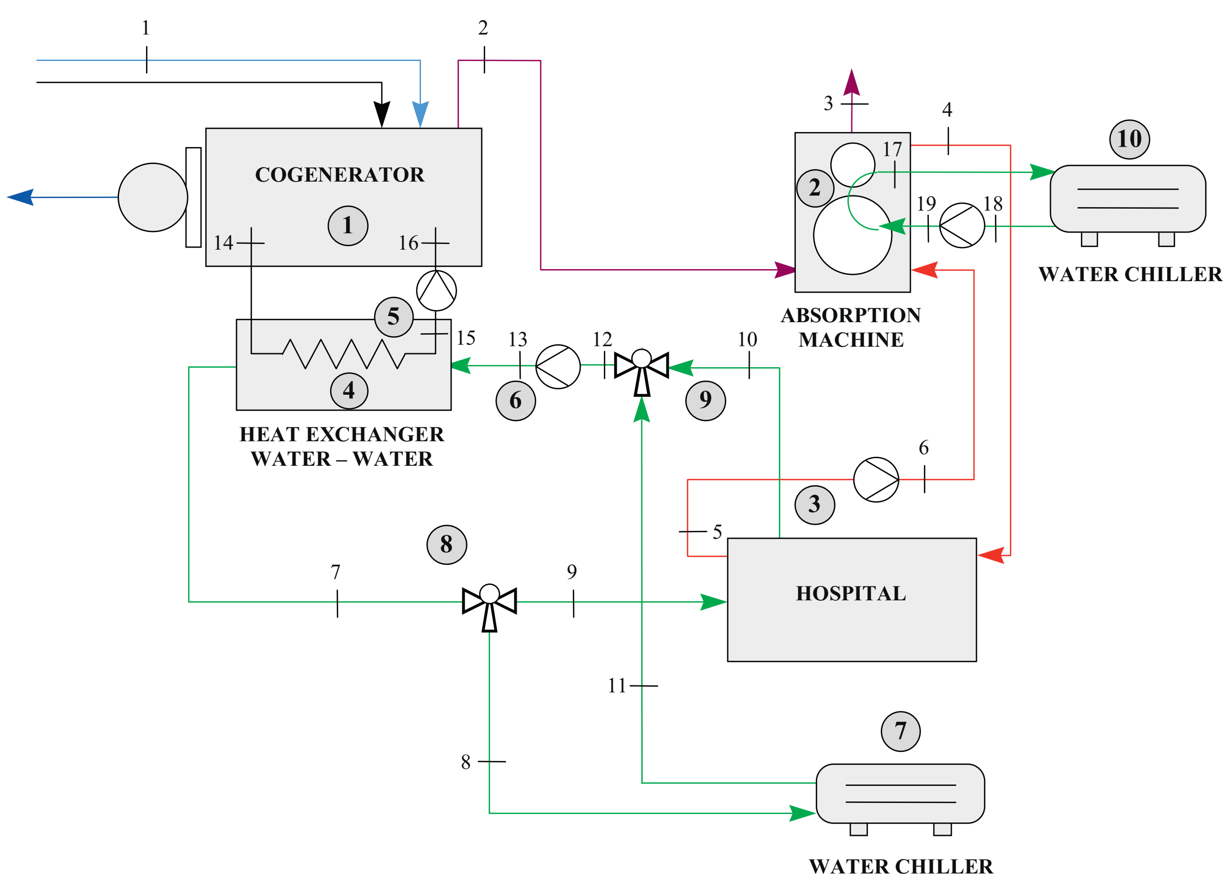


**Fig. 8.** Diagram of cogeneration plant using AICE and absorption machine.

**Table 5**
Costs of cogeneration products.

| | Electricity ($c_e$) (US$/kW h) | Steam ($c_s$) (US$/kW h) | Cold water ($c_{cw}$) (US$/kW h) | Hot water ($c_{hw}$) (US$/kW h) |
|---|---|---|---|---|
| Case 1 | 0.049755 | 0.043267 | 0.00000 | 0.016376 |
| Case 2 | 0.041973 | 0.047898 | 0.000000 | 0.012450 |
| Case 3 | 0.049130 | 0.044339 | 0.000000 | 0.014607 |
| Case 4a | 0.053340 | 0.000000 | 0.040326 | 0.016898 |
| Case 4b | 0.051953 | 0.000000 | 0.027631 | 0.014878 |

**Table 6**
Investments and maintenance for reference scenario.

| | Investments | | | Maintenance | | |
|---|---|---|---|---|---|---|
| | Steam ($I_{cb1}$) (US$) | Hot water ($I_{cb2}$) (US$) | Cold water ($I_{cr}$) (US$) | Steam ($c_{Mcb1}$) (US$/kW h) | Hot water ($c_{Mcb2}$) (US$/kW h) | Cold water ($c_{Mcr}$) (US$/kW h) |
| Case 1 | 86,373 | 33,669 | 0 | 0.000187 | 0.000318 | 0 |
| Case 2 | 32,536 | 33,669 | 0 | 0.000323 | 0.000318 | 0 |
| Case 3 | 73,261 | 33,669 | 0 | 0.000144 | 0.000318 | 0 |
| Case 4a | 0 | 0 | 541,660 | 0.000000 | 0.000318 | 0.000523 |
| Case 4b | 0 | 0 | 541,660 | 0.000000 | 0.000318 | 0.000523 |

**Table 7**
Costs of products for reference scenario.

| | Steam ($c_{cc1}$) (US$/kW h) | Hot water ($c_{cc2}$) (US$/kW h) | Cold water ($c_{cw}$) (US$/kW h) |
|---|---|---|---|
| Case 1 | 0.017354 | 0.018794 | 0.00000 |
| Case 2 | 0.018862 | 0.018794 | 0.00000 |
| Case 3 | 0.017554 | 0.018794 | 0.00000 |
| Case 4a | 0.000000 | 0.018794 | 0.03240 |
| Case 4b | 0.000000 | 0.018794 | 0.03240 |

### 5.2. Evaluation of the thermoeconomic functional diagram

According to [39], it is possible to evaluate thermoeconomic functional diagrams associated to physical diagrams (process diagrams) viewed in Figs. 7 and 8, such as shown in Figs. 9 and 10.

### 5.3. Determination of equations for exergetic functions

In this study, pipe losses will be despised in determination of exergetic functions associated to thermoeconomic functional diagrams, simplifying evaluations without invalidate this analysis.

Based on physical diagrams (Figs. 7 and 8) and thermodynamics properties values such as indicated before (Tables 9 and 10), it is possible to determine exergetic flow values in incremental base, which are associated to thermoeconomic functional diagrams (Figs. 9 and 10).

Proceeding in this way, exergetic functions associated to these processes can be represented through the expressions related in [39].

### 5.4. Determination of cost equations for thermoeconomic optimisation

As mentioned before, the objective of this optimisation method consists in minimize the exergetic production cost (EPC), which is defined through the costs diagram, being function of raw materials associated to process. In this study, diagrams of associated costs (Figs. 11 and 12) are the following.

#### 5.4.1. Cogeneration plant with AICE and HRSG (cases 1, 2, and 3)

In these cases, the EPC is determined through sum of generation costs (in exergetic base) from distinct tertiary energies. It is important to note that, for cases 1 and 3 (surplus generation), line 1 in Fig. 11 represents its costs diagram. In other way, for case 2 (slack operation), line 2 in Fig. 11 represents its associated exergetic costs diagram, expressed as Eqs. (29) and (30).

$$\mathrm{EPC} = c_e + c_s - c_{sur} + c_{hw} \tag{29}$$

$$\mathrm{EPC} = c_e + c_s - c_{ep} + c_{hw} \tag{30}$$

where:

$$c_e = \frac{I_{pl} - I_{hrsg} - I_{he}}{H \times Y_{1.3}} + c_{fuel} \times \frac{Y_{1.1} - (Y_{1.1} - Y_{(2.1)}) - Y_{4.2}}{Y_{1.3}} + c_{men} \tag{31}$$

$$c_s = \frac{I_{hrsg} f}{H \times Y_{22}} + c_{fuel} \times \frac{Y_{1.1} - Y_{2.1}}{Y_{2.2}} + c_{Mhrsg} \tag{32}$$

$$c_{hw} = \frac{I_{he} f}{H \times Y_{4.2}} + c_{fuel} + c_{Mhe} \tag{33}$$

$$c_{ep} = 0.070\,(\mathrm{US\$/kW\,h}) \tag{34}$$

**Table 8**
Annual benefit expected.

| Case # | Products profit | | | | Total benefit expected |
|---|---|---|---|---|---|
| | Electricity ($Pd_e$) (US$) | Steam ($Pd_s$) (US$) | Cold water ($Pd_{cw}$) (US$) | Hot water ($Pd_{hw}$) (US$) | Annual benefit ($R$) (US$) |
| 1 | −44,001 | −313,097 | 0 | 7098 | −350,000 |
| 2 | 268,779 | −80,992 | 0 | 18,624 | 206,411 |
| 3 | 82,482 | −252,675 | 0 | 12,290 | −157,903 |
| 4a | −638,959 | 0 | −138,609 | 5567 | −772,001 |
| 4b | −142,776 | 0 | 84,083 | 11,495 | −47,198 |

**Table 9**
Thermodynamics features from cases 1, 2, and 3.

| Point | Fluid | Case 1 | | | | | Case 2 | | | | | Case 3 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Flow (kg/s) | Pressure (kgf/cm$^2$) | Temp. (°C) | Enthalpy (kJ/kg) | Entrophy (kJ/kg °C) | Flow (kg/s) | Pressure (kgf/cm$^2$) | Temp. (°C) | Enthalpy (kJ/kg) | Entrophy (kJ/kg °C) | Flow (kg/s) | Pressure (kgf/cm$^2$) | Temp. (°C) | Enthalpy (kJ/kg) | Entrophy (kJ/kg °C) |
| 1 | Air | – | 1.0 | 25.00 | 71.26 | 0.5995 | – | 1.0 | 25.00 | 71.26 | 0.5995 | – | 1.0 | 25.00 | 71.26 | 0.5995 |
| 1 | Fuel | – | 1.0 | – | – | – | – | 1.0 | – | – | – | – | 1.0 | – | – | – |
| 2 | Gases | 12.5191 | 1.0 | 338.00 | 374.39 | – | 3.3389 | 1.0 | 310.00 | 341.11 | – | 10.0143 | 1.0 | 338.00 | 374.39 | – |
| 3 | Gases | 12.5191 | 1.0 | 167.00 | 177.71 | – | 3.3389 | 1.0 | 170.00 | 180.91 | – | 10.0143 | 1.0 | 173.00 | 184.33 | – |
| 4 | Steam saturated | 0.8222 | 7.5 | 167.80 | 2766.00 | 6.6850 | 0.2222 | 7.5 | 167.80 | 2766.00 | 6.6850 | 0.6000 | 7.5 | 167.80 | 2766.00 | 6.6850 |
| 5 | Condensate | 0.8222 | 6.0 | 97.15 | 407.00 | 1.2744 | 0.2222 | 6.0 | 97.15 | 407.00 | 1.2744 | 0.6000 | 6.0 | 97.15 | 407.00 | 1.2744 |
| 6 | Condensate | 0.8222 | 7.5 | 97.15 | 407.50 | 1.2740 | 0.2222 | 7.5 | 97.15 | 407.50 | 1.2740 | 0.6000 | 7.5 | 97.15 | 407.50 | 1.2740 |
| 7 | Water HT | 36.9726 | 1.5 | 60.00 | 251.20 | 0.8310 | 9.9702 | 1.5 | 60.00 | 251.20 | 0.8310 | 24.8086 | 1.5 | 60.00 | 251.20 | 0.8310 |
| 8 | Water HT | 34.1108 | 1.5 | 60.00 | 251.20 | 0.8310 | 7.1084 | 1.5 | 60.00 | 251.20 | 0.8310 | 21.9468 | 1.5 | 60.00 | 251.20 | 0.8310 |
| 9 | Water HT | 2.8618 | 1.5 | 60.00 | 251.20 | 0.8310 | 2.8618 | 1.5 | 60.00 | 251.20 | 0.8310 | 2.8618 | 1.5 | 60.00 | 251.20 | 0.8310 |
| 10 | Water LT | 2.8618 | 1.0 | 25.00 | 104.96 | 0.3673 | 2.8618 | 1.0 | 25.00 | 104.96 | 0.3673 | 2.8618 | 1.0 | 25.00 | 104.96 | 0.3673 |
| 11 | Water LT | 34.1108 | 1.0 | 25.00 | 104.96 | 0.3673 | 7.1084 | 1.0 | 25.00 | 104.96 | 0.3673 | 21.9468 | 1.0 | 25.00 | 104.96 | 0.3673 |
| 12 | Water LT | 36.9726 | 1.0 | 25.00 | 104.96 | 0.3673 | 9.9702 | 1.0 | 25.00 | 104.96 | 0.3673 | 24.8086 | 1.0 | 25.00 | 104.96 | 0.3673 |
| 13 | Water LT | 36.9726 | 2.0 | 25.00 | 105.05 | 0.3673 | 9.9702 | 2.0 | 25.00 | 105.05 | 0.3673 | 24.8086 | 2.0 | 25.00 | 105.05 | 0.3673 |
| 14 | Jacket water HT | 64.7020 | 1.0 | 90.00 | 376.90 | 1.1924 | 17.4479 | 1.0 | 90.00 | 376.90 | 1.1924 | 43.4150 | 1.0 | 90.00 | 376.90 | 1.1924 |
| 15 | Jacket water LT | 64.7020 | 0.5 | 70.00 | 293.00 | 0.9548 | 17.4479 | 0.5 | 70.00 | 293.00 | 0.9548 | 43.4150 | 0.5 | 70.00 | 293.00 | 0.9548 |
| 16 | Jacket water LT | 64.7020 | 2.0 | 70.00 | 293.10 | 0.9547 | 17.4479 | 2.0 | 70.00 | 293.10 | 0.9547 | 43.4150 | 2.0 | 70.00 | 293.10 | 0.9547 |

**Table 10**
Thermodynamics features from cases 4a and 4b.

| Point | Fluid | Case 4a | | | | | Case 4b | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Flow (kg/s) | Pressure (kgf/cm$^2$) | Temp. (°C) | Enthalpy (kJ/kg) | Entropy (kJ/kg °C) | Flow (kg/s) | Pressure (kgf/cm$^2$) | Temp. (°C) | Enthalpy (kJ/kg) | Entropy (kJ/kg °C) |
| 1 | Air | – | 1.0 | 25.00 | 71,262 | 0.5995 | – | 1.0 | 25.00 | 71.26 | 0.5995 |
| 1 | Fuel | – | 1.0 | – | – | – | – | 1.0 | – | – | – |
| 2 | Gases | 18.7787 | 1.0 | 338.00 | 374,389 | – | 10.4326 | 1.0 | 338.00 | 374.39 | – |
| 3 | Gases | 18.7787 | 1.0 | 170.05 | 180,959 | – | 10.4326 | 1.0 | 174.35 | 185.77 | – |
| 4 | Cold water LT | 119.7038 | 2.0 | 7.00 | 29,580 | 0.1062 | 119.7038 | 2.0 | 7.00 | 29.58 | 0.1062 |
| 5 | Cold water HT | 119.7038 | 1.5 | 12.00 | 50,540 | 0.1805 | 119.7038 | 1.5 | 12.00 | 50.54 | 0.1805 |
| 6 | Cold water HT | 119.7038 | 2.0 | 12.00 | 50,590 | 0.1805 | 119.7038 | 2.0 | 12.00 | 50.59 | 0.1805 |
| 7 | Water HT | 40.5601 | 1.5 | 60.00 | 251,200 | 0.8310 | 26.6719 | 1.5 | 60.00 | 251.20 | 0.8310 |
| 8 | Water HT | 37.6983 | 1.5 | 60.00 | 251,200 | 0.8310 | 23.8102 | 1.5 | 60.00 | 251.20 | 0.8310 |
| 9 | Water HT | 2.8618 | 1.5 | 60.00 | 251,200 | 0.8310 | 2.8618 | 1.5 | 60.00 | 251.20 | 0.8310 |
| 10 | Water LT | 2.8618 | 1.0 | 25.00 | 104,960 | 0.3673 | 2.8618 | 1.0 | 25.00 | 104.96 | 0.3673 |
| 11 | Water LT | 37.6983 | 1.0 | 25.00 | 104,960 | 0.3673 | 23.8102 | 1.0 | 25.00 | 104.96 | 0.3673 |
| 12 | Water LT | 40.5601 | 1.0 | 25.00 | 104,960 | 0.3673 | 26.6719 | 1.0 | 25.00 | 104.96 | 0.3673 |
| 13 | Water LT | 40.5601 | 2.0 | 25.00 | 105,050 | 0.3673 | 26.6719 | 2.0 | 25.00 | 105.05 | 0.3673 |
| 14 | Jacket water HT | 70.9802 | 1.0 | 90.00 | 376,900 | 1.1924 | 46.6759 | 1.0 | 90.00 | 376.90 | 1.1924 |
| 15 | Jacket water LT | 70.9802 | 0.5 | 70.00 | 293,000 | 0.9548 | 46.6759 | 0.5 | 70.00 | 293.00 | 0.9548 |
| 16 | Jacket water LT | 70.9802 | 2.0 | 70.00 | 293,100 | 0.9547 | 46.6759 | 2.0 | 70.00 | 293.10 | 0.9547 |
| 17 | Absorber water HT | 303.8636 | 2.0 | 45.00 | 188,590 | 0.6385 | 219.4570 | 2.0 | 45.00 | 188.59 | 0.6385 |
| 18 | Absorber water LT | 303.8636 | 1.5 | 40.00 | 167,670 | 0.5724 | 219.4570 | 1.5 | 40.00 | 167.67 | 0.5724 |
| 19 | Absorber water LT | 303.8636 | 2.0 | 40.00 | 167,710 | 0.5724 | 219.4570 | 2.0 | 40.00 | 167.71 | 0.5724 |

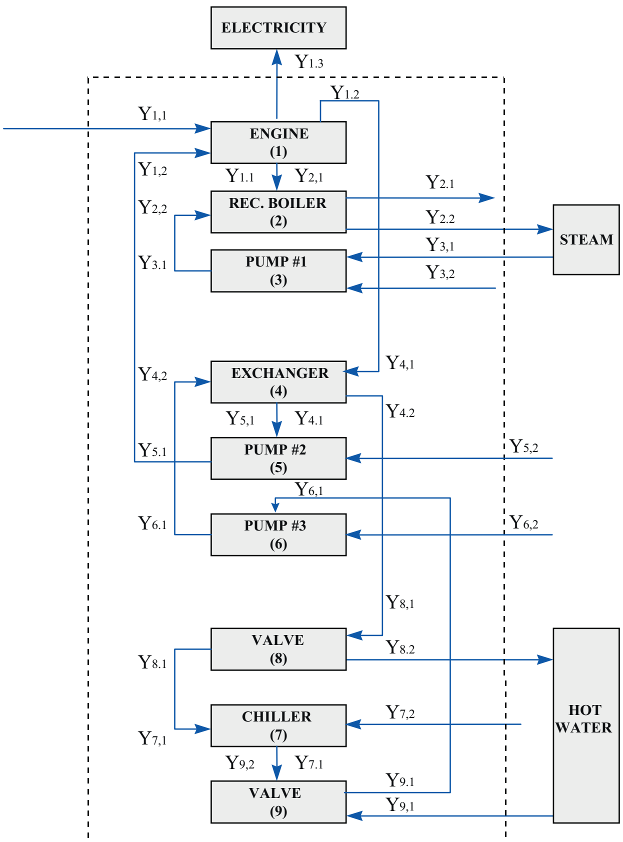


Fig. 9. Functional diagram for AICE associated to recovery boiler cases.

$$c_{sur} = 0.035\,(\text{US\$/kW h}) \quad (35)$$

*5.4.2. Cogeneration plant with AICE and absorption machine (cases 4a and 4b)*

For these cases, the EPC is determined such as an analogue way, however exergetic cost of steam production ($c_s$) is replaced through exergetic cost of cold water production ($c_{cw}$).

$$\text{EPC} = c_e + c_{cw} - c_{sur} + c_{hw} \quad (36)$$

$$c_{cw} = \frac{I_{am} f}{H \times Y_{2.2}} + c_{fuel} \times \frac{Y_{1.1} - Y_{2.1}}{Y_{2.2}} + c_{Mam} \quad (37)$$

Table 11 shows exergetic costs associated to cogeneration products and the values of EPC for five cogeneration cases considered for the hospital.

According to the final value of EPC is possible to observe these points:

- case 1 (AICE and recovery boiler) is the most efficient plant under exergoeconomic point of view: it can produce 2960 kJ/h of steam and still hot water;
- cases 4a and 4b have their EPC considerable increased because absorption machines, thus they need several heat dissipaters;
- case 2 is the best plant in an energoeconomic behaviour, however is third best option in an exergoeconomic way.

## 6. Ecological efficiency analysis

The ecological efficiency evaluates the pollutant amount of a system, considering gases emissions per kg of fuel used. This efficiency is ranged between 0 and 1; where an ecological efficiency equal to 0 means 100% of environmental impact, or high polluter, and an efficiency equal to 1 means 0% of environmental impact, or non-polluter.

Cardu and Baica [48,49] had introduced the concept of carbon dioxide equivalent [$(CO_2)_e$], based on maximum concentration allowed for $CO_2$, which is 10,000 mg/m$^3$. The equivalent coefficients for some pollutants, in kg per kg of fuel (kg/kg$_{fuel}$), called global warming potential (GWP), are related according

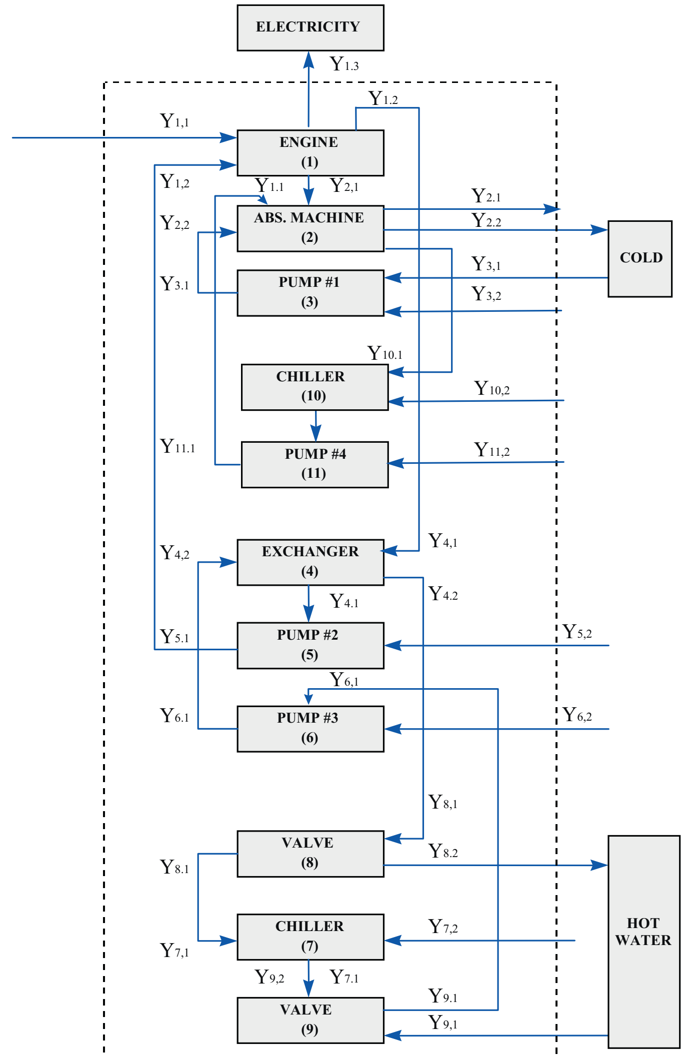


Fig. 10. Functional diagram for AICE associated to absorption machine cases.

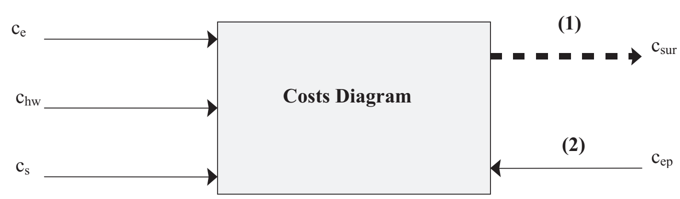


Fig. 11. Costs diagram for AICE associated to recovery boiler cases.


Fig. 12. Costs diagram for AICE associated to absorption machine cases.

**Table 11**
Results of thermoeconomic analysis.

| Case | $c_{ep}$ (US$/kW h) | $c_{sur}$ (US$/kW h) | $c_e$ (US$/kW h) | $c_s$ (US$/kW h) | $c_{hw}$ (US$/kW h) | $c_{cw}$ (US$/kW h) | EPC (US$/kW h) |
|---|---|---|---|---|---|---|---|
| 1 | 0.07 | 0.035 | 0.05839 | 0.03787 | 0.01283 | 0.00000 | 0.07410 |
| 2 | 0.07 | 0.035 | 0.05401 | 0.03545 | 0.01689 | 0.00000 | 0.17635 |
| 3 | 0.07 | 0.035 | 0.05918 | 0.04127 | 0.01351 | 0.00000 | 0.07900 |
| 4a | 0.07 | 0.035 | 0.05986 | 0.00000 | 0.01271 | 0.27045 | 0.30800 |
| 4b | 0.07 | 0.035 | 0.05909 | 0.00000 | 0.01336 | 0.24372 | 0.28120 |

to Eq. (38) [50–52].

$$(CO_2)_e = CO_2 + 1.9(CO) + 25(CH_4) + 50(NO_x) + 80(SO_2) + 67(PM) \quad (38)$$

An indicator is proposed by [48] to quantify environmental impact and it is defined as the difference between carbon dioxide equivalent of fuel and its lower heating value. This indicator is called pollution indicator represented by $\Pi_g$, Eq. (39).

$$\Pi_g = \frac{(CO_2)_e}{LHV} \quad (39)$$

where: $(CO_2)_e$: carbon dioxide equivalent (kg/kg$_{fuel}$); LHV: lower heating value of fuel (MJ/kg$_{fuel}$); $\Pi_g$: pollution indicator (kg/MJ).

Relating carbon dioxide emitted by fuel combustion process with its lower heating value, Cardu and Baica [48] make possible comparison between different fuels. However a fuel can have a high lower heating value and to emit a wide amount of pollutants into atmosphere or has negligible, or null, emissions of noxious gases, but cannot have the energy required to obtain a good efficiency in an industrial process.

Based on assumption that the best fuel is one that has the lowest pollution indicator, [48] propose a more complex and dimensionless index that expresses the ecological component of noxious gases emitted into atmosphere from the combustion of a fuel compared to useful energy produced in thermal power plants. The indicator proposed is called ecological efficiency ($\varepsilon$), such as Eq. (40).

$$\varepsilon = \left[\frac{0.204 \times \eta_{system}}{\eta_{system} + \Pi_g} \times \ln(135 - \Pi_g)\right] \quad (40)$$

There are three main equipments used in cases studied: AICE, HRSG, and absorption machine. These equipments will have their ecological efficiency evaluated, in order to estimate a global ecological efficiency for the sets proposed.

Table 12 shows pollutant emission values for natural gas used into AICE. These values applied to Eq. (39) provides the pollution indicator, which associated to LHV and system efficiency ($\eta_{system}$), evaluates ecological efficiency for AICE with natural gas.

Applying values from Table 12 to Eq. (40) is obtained 95.69 as ecological efficiency value for natural gas with a lower heating value of 9400 kcal/m$^3$ (39,355.92 kJ/kg), in accordance with COMGAS [53], which is a company that supports Sao Paulo State region with natural gas. The AICE efficiency adopted is 20% for a natural gas engine.

**Table 12**
Results of pollutant emissions for natural gas [52].

| Pollutant emission kg/kg of fuel | Natural gas |
|---|---|
| $(CO_2)_e$ | 2.769 |
| PM | $304 \times 10^{-6}$ |
| $NO_X$ | $856 \times 10^{-6}$ |
| $SO_2$ | $25.32 \times 10^{-6}$ |
| $CO_2$ | 2.7038 |
| Total (kg/kg of fuel) | 2.7049 |

For heat recovery steam generator (HRSG), in a system with natural gas as fuel and efficiency of 80% [54]. In this case, ecological efficiency is 95.9%.

The coefficient of performance for the absorption machine is 0.7 [55]. This value is equivalent to its thermal efficiency. Considering the absorption machine started by exhausted gases from AICE, are used the same pollutant emissions of natural gas [56]. So, it is obtained an ecological efficiency value equal to 95%.

## 7. Conclusion

Along all analysis accomplished for this work, it was possible to observe a variation about the best choice for optimal cogeneration plant, considering aspects approached, with considerable changes, in conclusions.

The most important facts are:

(a) The most efficient plant under energy balance point of view is the cogeneration plant that associate AICE with double effect absorption machine (case 4b), where is possible to achieve a global efficiency around 58%.
(b) Through economic viability analysis, which is based on searching the bigger annual benefit or receipt expected, in function of expenditure with energy before and after insertion of cogeneration, is possible to observe that the best alternative under an energoeconomic point of view is the case 2, which produces the steam required in the kitchen and hot water for sanitary use as sub-products. This case presented a global efficiency around 55%. In summary:

(a) with an annual interest rate at 12% and a payback of five years, case 2 is the unique viable alternative, occurring for interest rates up to 20% per year;
(b) case 4b, with a payback at five years, is viable with interest rates up to 8.5%, with viability guaranteed for a minimum surplus electricity sale price of 0.035 US$/kW h.

The actual Brazilian energy policy does not guarantee this price for surplus electricity sale, what makes difficult the economic viability for cogeneration projects working with surplus production.

(c) After to accomplish an exergoeconomic analysis, whose main objective was to appraise economically the intrinsic inefficiencies for thermal systems, inserting economical aspects and the exergy concepts as a tool to choose optimal cogeneration plant (through the definition of exergetic production cost), the case 1 appears such as the best cycle to be established in the hospital. As mentioned before, this conclusion is contradictory to the energetic analyse and still indicates that:

(c) The absorption machines joint a considerable increase of exergetic cost associated to the cogeneration plant;
(d) The plant proposed in case 2, which in energoeconomic analysis is presented as the most profitable, take down to third position after the exergoeconomic analysis, based on exergetic production cost (EPC).

Hence, finally is possible to conclude that the insertion of cogeneration systems for the hospital studied is viable, obeying the following features:

- under energoeconomic point of view, the case 2 is the optimal plant;
- under exergoeconomic point of view, the case 1 is the optimal plant, considering the minimal irreversibilities aspect.

Considering 95% as the value established such good for ecological efficiency, all sub-systems and cases studied presented values ranging from 95% to 95.9%, then they are considered as ecological efficient.

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